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Article

The right of nature to dispose of its salts

El derecho de la naturaleza de disponer de sus residuos salinos

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Abstract

Ions of sodium and calcium are produced by lithospheric disintegration in quantities far exceeding those that could possibly be assimilated by the terrestrial biosphere. In exorheic drainages, the resulting waste has been (and is being) transported to the ocean by streams and rivers. In endorheic drainages, it has collected in the interior of continents, producing closed salt basins. In general, exorheism is preferable to endorheism because it leads to healthier and more diverse ecosystems. Irrigation converts runoff into evaporation, reducing the amount of water available for salt flushing. At the same time, particularly in arid and semiarid regions where it is most needed, irrigation mobilizes new

salts through the additional biodegradation of geologically young soils. At the limit, when all runoff is sequestered and converted to evaporation, there is no water left to carry the salts to the ocean. As the system is gradually driven towards this limit, it becomes unsustainable, not for lack of water to support the vegetation, but for lack of water to flush the salts. In accordance with hydrologic science, we posit that nature had a different plan: on average, two-thirds of the available water for the ecosystem and the remaining one-third for flushing all salts, regional and new. The misguided strategy of retaining all runoff, on the grounds that it constitutes "precious" water, could only lead to the eventual conversion of peripheral continental basins into artificial, salt-infested basins.

Keywords: Salt, salinization, right of nature, salt balance.

Resumen

Iones de sodio y calcio se producen de forma constante por la desintegración de la litósfera en cantidades muy por encima de las que podrían ser asimiladas por la biósfera terrestre. En drenajes exorreicos, los residuos salinos resultantes han sido (y están siendo) transportados al océano por los ríos. Por otro lado, en drenajes endorreicos, la producción de sal se ha acumulado a través de milenios en el interior de los continentes. En general, el exorreísmo es preferible al endorreísmo, pues lleva a ecosistemas más diversos. La irrigación convierte la escorrentía en evapotranspiración, reduciendo así la cantidad de agua disponible para el lavado de las sales. Al mismo tiempo, en regiones áridas, la irrigación moviliza nuevas sales debido al intemperismo adicional en suelos jóvenes. En el límite, cuando toda la escorrentía es secuestrada y convertida en evaporación, no queda ningún agua para llevar las sales al océano. De manera eventual, el sistema se vuelve insostenible, no por falta de agua para la vegetación, sino por falta de agua para la eliminación de las sales. Siguiendo los principios de hidrología, aquí postulamos que la naturaleza tenía un plan diferente: en promedio, dos tercios del agua disponible para el ecosistema, y el tercio restante para el lavado de las sales. La estrategia equivocada de retener toda la escorrentía con el argumento de que constituye un recurso "muy valioso" sólo puede conducir a la eventual conversión de las cuencas continentales periféricas en cuencas artificialmente infestadas con sal.

Palabras clave: sal, salinización, derecho de la naturaleza, balance de sales.

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Origin of Ocean Salt

The total amount of water in the world has been estimated at 1 500 000 000 km^3 (Penman, 1970). Of this total, about 97%, or 1 455 000 000 km^3, corresponds to the oceans. The oceans contain dissolved salts at concentrations averaging 35 kg per m^3 of seawater. Thus, by weight, the total amount of salt in the oceans is about 50×10^{15} metric tons, an enormeous quantity by any measure (Swenson, 2015). Scientists are not sure of the source of all this salt, but it is generally agreed that most of it must have originated as constituents of terrestrial rocks (i.e., in the lithosphere), which degraded over geologic time and was transported to the oceans by the flow of streams and rivers (Pillsbury, 1981).

Of all salt ions dissolved in the oceans, sodium (Na^+) and chloride (Cl^-) alone account for about five out of six parts (5/6) (by weight). In elemental form, both sodium metal (Na) and chlorine gas (Cl) are highly reactive. However, when combined into the compound sodium chloride, the latter turns out to be highly stable.

The primary industrial application of sodium chloride is for the transport and sale of its constituents. Large quantities of sodium chloride are extracted from ocean water and salt lakes for use as raw material for the production of chlorine gas (Cl) and sodium hydroxide (caustic soda) (NaOH). As an example, Figure 1 shows the salt works at Guerrero Negro, Baja California Sur, Mexico, the world's largest.

Figure 1. (left) Coastal evaporation lagoons at the Guerrero Negro salt Works (Visualab, 2015). (right) Production of bulk sodium chloride (trotamexico.com, 2015).

Nature of Salt

Salts are chemical compounds that originate from the reaction of an acid and a base. They are composed of cations (positively-charged ions) and anions (negatively-charged ions), such that the combination is electrically neutral.

Salt ions may be inorganic or organic. The most common inorganic salt cations are sodium (Na^+), magnesium (Mg^+), potassium (K^+), and calcium (Ca^+). These ions are grouped together by atomic number in the Periodic Table of Elements. Their atomic numbers are 11, 12, 19, and 20, respectively.

The most common inorganic salt anion is chloride (Cl^-), with atomic number 17; the other inorganic elemental salt anion is flouride (F^-), with atomic number 9. Sodium and chloride are by far the most abundant salt ions in the oceans (Deevey, 1970). In its mineral state, sodium chloride is referred to as halite, and in common usage it is called table salt.

Source of Salts

Nature is composed of four spheres: (1) biosphere, (2) lithosphere, (3) hydrosphere, and (4) atmosphere. These interact with each other to form the ecosphere, the sum total of nature, encompassing all living and non-living things. The lithosphere contains large quantities of the four most common inorganic salt cations (Na^+, Ca^+, Mg^+, and K^+); however, it contains only very small amounts of the elemental salt anions (chloride Cl^- and fluoride F^-) (Deevey, 1970). Thus, for salt compounds to form, the anions must be supplied by at least one of the other spheres. Chloride is amply supplied by the hydrosphere (Deevey, 1970), and in minute quantities (aerosols) it is also supplied by the oceans to the atmosphere, eventually to return to the hydrosphere through precipitation.

Table 1 shows the relative presence of the four most common salt cations in the lithosphere. The two largest ionic components of the lithosphere are oxygen (O^-) and silicon (Si^+), at 60.4 and 20.5% of atoms, respectively. The inorganic salt cations (Na^+, Ca^+, Mg^+, and K^+) constitute 2.49, 1.88, 1.77, and 1.37% of atoms in the lithosphere, respectively, (Table 1, column 3) (Deevey, 1970). Column 7 of Table 1 shows that the inorganic salt cations constitute about 11.1% of the lithosphere, by weight. This means that for every metric ton (1 000 kg) of lithospheric rocks disaggregated by weathering, erosion, and other natural processes, about 111 kg of salt cations are released to the other spheres. Column 7 shows that the four inorganic salt cations are about evenly present in the lithosphere.

Table 1. Relative presence of the four most common salt cations in the lithosphere.

Elemental cation or anion	**Symbol**	**% of atoms**	**Molecular Weight (MW)**	**% × MW (all cations)**	**% × MW (salt cations)**	**% of total (only salt cations)**
Oxygen	O^-	60.40	15.99	966.340	-	-
Silicone	Si^+	20.50	28.09	575.845	-	-
Aluminum	Al^+	6.20	26.98	167.276	-	-

Hydrogen	H^+	2.92	1.01	2.949	-	-
Sodium	Na^+	2.49	22.99	57.245	57.245	2.77
Calcium	Ca^+	1.88	40.08	75.350	75.350	3.65
Magnesium	Mg^+	1.77	24.31	43.029	43.029	2.08
Potasium	K^+	1.37	39.10	53.567	53.567	2.59
Iron	Fe^+	1.90	55.85	106.115	-	-
Titanium	Ti^+	0.27	47.90	12.933	-	-
Carbon	C^+	0.16	12.01	1.922	-	-
Phosphorous	P^+	0.08	30.97	2.478	-	-
Sulfur	S^+	0.04	32.06	1.282	-	-
Total	-	99.98	-	2066.331	229.191	11.09

What fraction of this amount (111 kg per metric ton) is incorporated into the three other spheres? Sodium is mostly absent from the biosphere and atmosphere, but significantly present in the hydrosphere. Calcium, magnesium, and potassium are present in the biosphere and hydrosphere, but absent from the atmosphere. (Note that nitrogen, an important constituent of the biosphere, is largely absent from the lithosphere, its primary source being the atmosphere) (Deevey, 1970).

After its release from the lithosphere, sodium is absorbed only by the hydrosphere, while calcium, magnesium, and potassium are taken up by both the biosphere and hydrosphere. Notably, sodium is not taken by the biosphere in any appreciable quantity, compared to the other salt cations (Deevey, 1970). These observations are summarized in Table 2.

Table 2. Source and destination of the four most common salt cations.

Elemental salt cation	Symbol	Origen	Destination		
			Biosphere	Hydrosphere	Atmosphere
Sodium	Na^+	Lithosphere		✓	-
Calcium	Ca^+	Lithosphere	✓	✓	-
Magnesium	Mg^+	Lithosphere	✓	✓	-
Potasium	K^+	Lithosphere	✓	✓	-

There is ample evidence to suggest that significant amounts of potassium and magnesium are taken up by the terrestrial biosphere, while most calcium and sodium are released by the biosphere, only to join the continental hydrosphere. Potassium ions are essential for the functioning of all living cells. One atom of magnesium lies at the center of every chlorophyll molecule (Deevey, 1970).

The hydrosphere is selective in its use of salt cations. Table 3 compares the percentages of ionic salt content in ocean water and river water (Swenson, 2015). As shown, in ocean water, the predominant salt ions are chloride (Cl^-) and sodium (Na^+). While in river water the predominant salt ions are bicarbonate (HCO_3^-), calcium (Ca^+), and sulfate (SO_4^-). Chloride (Cl^-) and sodium (Na^+) are next on the list, also with significant percentages.

Table 3. Percentages of ionic salt content in ocean wáter and river water.

Ion	Symbol	Saltwater	Freshwater
Clorine	Cl^-	55.16	8.64
Sodium	Na^+	30.53	6.98
Sulfate	SO_4^-	7.67	12.41
Magnesium	Mg^+	3.72	4.54

Calcium	Ca^+	1.19	16.62
Potasium	K^+	1.11	2.55
Bicarbonate	HCO_3^-	0.42	31.90
Bromide	Br^-	0.20	-
Silicon	SiO_2^-	-	14.51
Nitrate	NO_3^-	-	1.11
Iron	Fe^+	-	0.74
Total	**-**	**100.00**	**100.00**

There are various reasons for this selectivity. Bicarbonate and sulfate appear in river water as the main products of biodegradation. Calcium and sodium appear in river water because they are not significantly used by the biosphere, which wastes the surplus calcium and sodium by leaching them into river water. Potassium and magnesium also show up in river water, but at smaller percentages than calcium and sodium.

Tables 4a to 4c present the percentage of the four most common salt cations in: (a) the lithosphere, (b) river water, and (c) ocean water, respectively. As shown, the presence of potassium and magnesium in the lithosphere is much greater than in river water. Calcium appears to be little affected by the biosphere, and the same follows for sodium. As a result of the biospheric sequestration of potassium and magnesium, the quantity of inorganic salt cations actually entering river water is much less than that in their lithospheric source.

Table 4a. Percentage of the four most common salt cations in the lithosphere.

Elemental salt cation	**Symbol**	**% of atoms**	**Molecular weight (MW)**	**% of atoms × MW**	**% of salt cations in the lithosphere**
Sodium	Na^+	2.49	22.99	57.245	24.98

Calcium	Ca^+	1.88	40.08	75.350	32.88
Magnesium	Mg^+	1.77	24.31	43.029	18.77
Potasium	K^+	1.37	39.10	53.567	23.37
Total				229.191	100.00

Table 4b. Percentage of the four most common salt cations in river water.

Elemental salt cation	Symbol	% of solids in freshwater	% of salt cations in freshwater
Sodium	Na^+	6.98	22.74
Calcium	Ca^+	16.62	54.16
Magnesium	Mg^+	4.54	14.79
Potasium	K^+	2.55	8.31
Total		30.69	100.00

Table 4c. Percentage of the four most common salt cations in ocean water.

Elemental salt cation	Symbol	% of solids in ocean water	% of salt cations in ocean water
Sodium	Na^+	30.53	83.53
Calcium	Ca^+	1.19	3.25
Magnesium	Mg^+	3.72	10.18
Potasium	K^+	1.11	3.04
Total		36.55	100.00

A value of 50% may be considered a rough estimate of the percentage of lithospheric salt cations delivered to river water. This would mean that about 55 kg of salt cations are delivered to river water for every metric ton of weathered/eroded rock, a sizable quantity by any measure. By comparison, the burning of one metric ton of organic matter produces only roughly 12 kg of ash minerals (Deevey, 1970). This underscores the different chemical natures of the hydrosphere (river water) and biosphere.

While both calcium and sodium are wasted by the terrestrial biosphere, which explains their presence in river water, the absence of dissolved calcium in ocean water (Table 4c) requires further explanation. The contradiction is resolved by the oceanic biosphere acting as a sink for calcium, which is used by a variety of marine organisms for the construction of shells and skeletons (Swenson, 2015).

Table 5 summarizes the findings of Table 4. Sodium is the only inorganic salt cation that remains in solution in the oceans. There is no biological process known to remove sodium ions from the oceans (Swenson, 2015). Together with chloride, a constituent of the hydrosphere, these two ions represent 85.7% of all dissolved solids in ocean water (the sum of the first two lines of column 3, Table 3). The extremely high solubility of sodium chloride in water, the highest of any known substance, all but guarantees that once dissolved in river water, sodium chloride remains in solution as it reaches its terminus in the oceans, and for all time beyond.

Table 5. Relative presence of the four most common salt cations in the lithosphere and hydrosphere.

Elemental salt cation	**Symbol**	**Percentage of presence**		
		Lithosphere	**Hydrosphere**	
			In freshwater	**In ocean water**
Sodium	Na^+	24.98	24.74	83.53
Calcium	Ca^+	32.88	54.16	3.25
Magnesium	Mg^+	18.77	14.79	10.18
Potasium	K^+	23.37	8.31	3.04
Total	-	**100.00**	**100.00**	**100.00**

The Right of Nature

The source of salt ions having been established and their destination clarified, it is concluded that nature (in this case, the terrestrial biosphere) has reserved for itself the right to dispose of its salt waste. Calcium and sodium cations are largely wasted by the terrestrial biosphere, since, like any other waste, they are supplied in quantities far exceeding the actual demand.

After reaching the ocean, calcium is used up by marine organisms, leaving sodium--and chloride, its ubiquitous partner--as the only true wastes by nature. In peripheral continental drainages with exorheic (outbound) flows, streams and rivers serve the purpose of flushing the surplus salts to the ocean. This fundamental right of nature has occurred since the beginning of time (Pillsbury, 1981).

Exorheic drainage basins, typically located in the periphery of continents, are effectively able to flush their salts to the ocean. On the other hand, endorheic drainages, often located in the interior of continents, are unable to flush their salts and, instead, accumulate them over geologic time. Whether a given basin is exorheic or endorheic will depend on the continental location and local/regional geomorphology (Ponce, 2014). What is certain is that fully exorheic basins are effectively in salt balance, with no net accumulation of salts, while endorheic drainages are not.

In general, endorheism accumulates salts, impeding the development of diverse ecosystems, and thus, hampering life. Conversely, exorheic drainages flush the surplus salts, enabling them to continue to support normal life in its myriad of forms. The larger the continental mass, the greater the chance for endorheism (Figure 2). Yet, exorheic drainages have a clear advantage over endorheic ones with regard to salt balance.

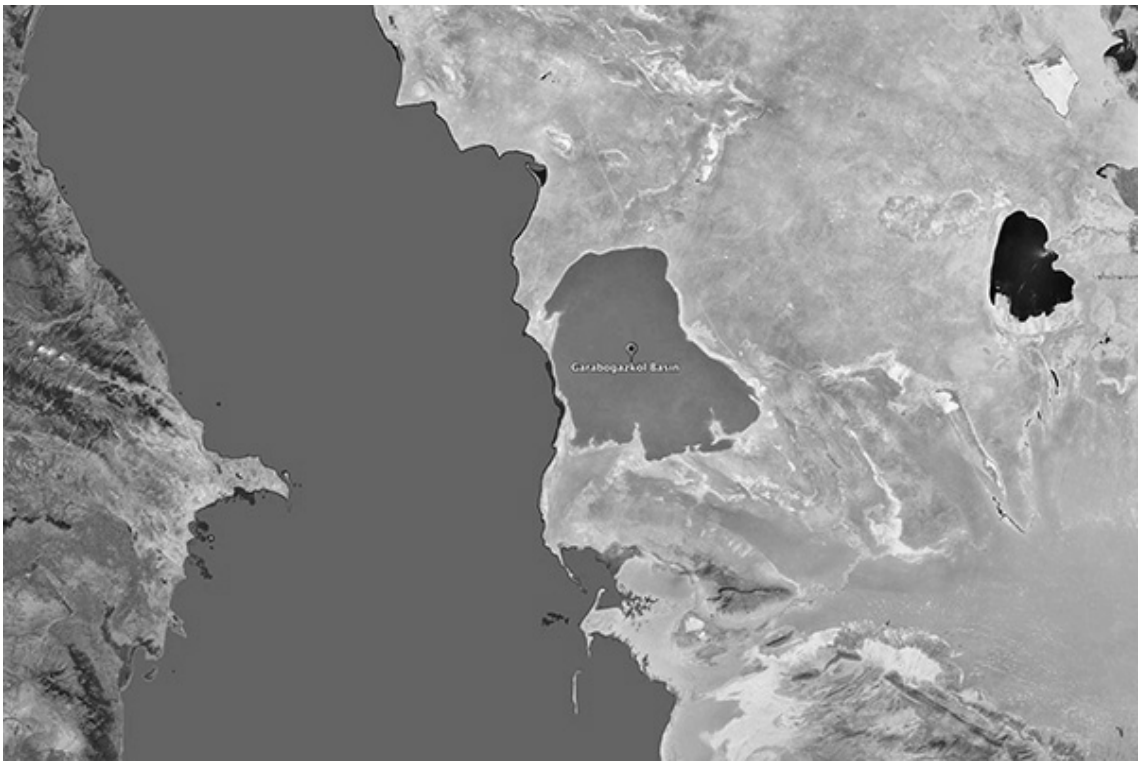

Figure 2. Garabogazköl basin in Turkmenistan, Asia, the terminus of the Caspian Sea drainage. The salinity of the basin is 345 kg per m^3, among the largest for endorheic lakes and about ten times greater than that of the oceans (Google Earth, 2015).

In summary, for peripheral continental basins, rivers serve the purpose of transporting the unwanted salts to the ocean, where they remain out of sight and out of mind. In this context, rivers are seen as natural exporters of salt to the ocean (Pillsbury, 1981). The reduction of river flow by anthropogenic catchment (and its eventual conversion to evaporation through irrigation) has the effect of gradually changing an exorheic drainage into an endorheic one, thus compromising the natural salt balance. Yet, this is precisely what humans have been doing in recent times, particularly during the past century.

The Design of Nature

The hydrologic cycle is the primordial engine of nature. It consists of three fluxes: (1) precipitation, (2) evaporation, and (3) runoff. After it hits the ground surface, precipitation separates into runoff and evaporation. Through runoff, water is returned directly to the ocean where it originated. Through evaporation, water is returned to the atmosphere, shortcutting the hydrologic cycle.

On a global annual basis, about one-third of precipitation becomes runoff, while the remaining fraction (about two-thirds) is converted to water vapor and returned to the atmosphere. On an annual basis, the ratio of runoff to precipitation is referred to as the yield runoff coefficient, *K*. This coefficient varies widely, from as little as 0.02, to as much as 0.93 in highly unusual cases (L'vovich, 1979).

The yield runoff coefficient, *K*, must not be confused with the event runoff coefficient, *C*, which is used in urban hydrology. While *K* is a function of climate, *C* is a function of degree of imperviousness of the watershed in question. Figure 3 shows an approximate conceptual model of runoff coefficients, wherein *K* is a function of Pma/Pagt, the ratio or mean annual precipitation to annual global terrestrial precipitation. The latter is approximated as Pagt = 800 mm, or 32 in (Ponce et al., 2000).

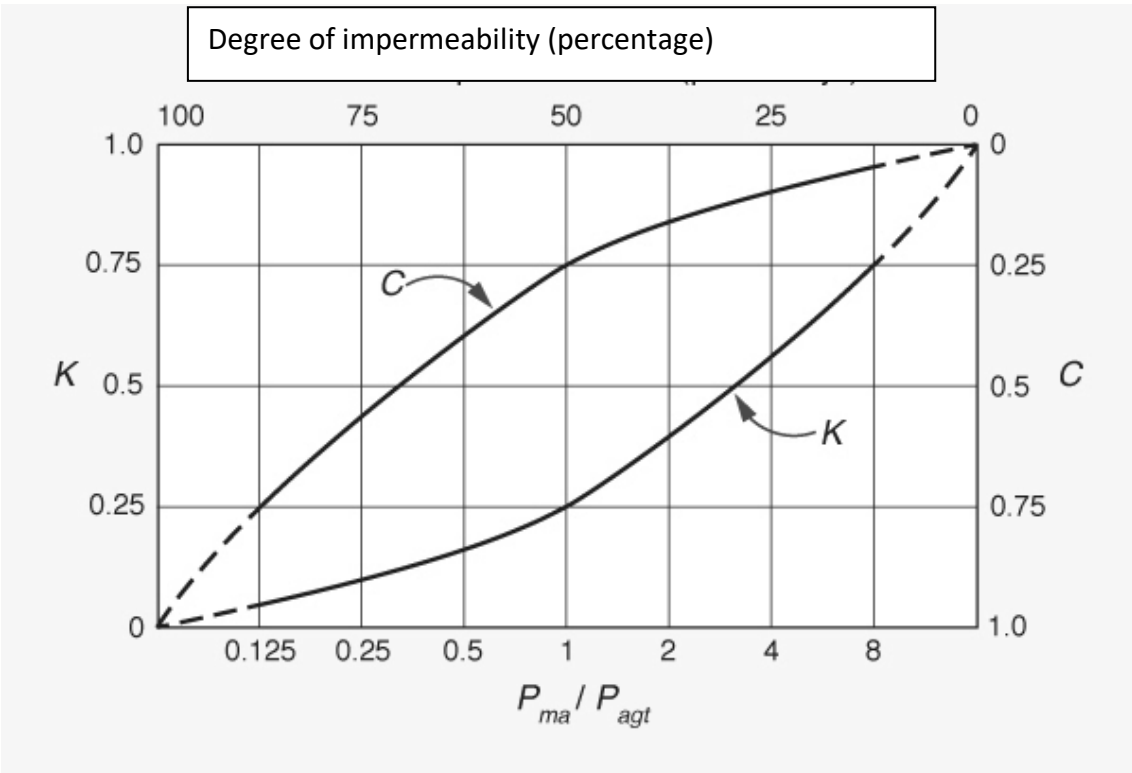

Figure 3. Conceptual model of runoff coefficients.

Nature designed the hydrologic cycle so that evaporation and runoff would share in the precipitation. In one extreme, for $K = 0$, runoff is zero and evaporation is at a maximum; it follows that there is no natural means to flush the salts out of the drainage basin. Thus, salts accumulate without limit, substantially impairing life processes and limiting ecosystem diversity. This is the case of the endorheic basins, typically located in the interior of continents, particularly where runoff has not been able to find an outlet to the nearest ocean. The end result is a salt desert, where life is limited, not only due to lack of water, but also to the endless accumulation of salt. (An extreme example of anthropogenic endorheism is that of the Salton Sea, in California, where a salt lake has been created over the past 80 years by the collection of agricultural drainage in a naturally occurring depression, the Salton Sink. Salts continue to accumulate in the Salton Sea, with no apparent end in sight.) (Ponce, 2005).

On the other extreme, for $K = 1$, evaporation is zero and runoff is at a maximum. Under this scheme, the system is clearly unable to sustain any vegetation. Vegetation requires a constant supply of moisture in order for vascular plants to maintain turgor, and thus, avoid wilting. The end result is also a desert, since there is no possibility for the establishment of vegetation.

The foregoing cases are unrealistic extremes, presented here only for the sake of discussion. In actuality, nature splits the water made available by precipitation into two distinct fractions: one for evaporation and another for runoff. The actual amounts depend significantly on climate, but also on the local and regional geology, geomorphology, and continental location.

Where runoff is more than the average, vegetation tends to cover the entire ground surface; thus, evaporation proceeds through two paths: (1) through vegetation (evapotranspiration) and (2) from water bodies. In this case, a typical range is about $0.4 \leq K \leq 0.6$. An example of this case is the Amazon rainforest basin (Figure 4), for which $K = 0.52$, measured at the Obidos Narrows in Para, Brazil.

Figure 4. The Amazon rainforest (Wikimedia Commons, 2015).

Conversely, where runoff is less than the average, vegetation does not cover the entire ground surface; thus, evaporation proceeds through three paths: (1) through vegetation (evapotranspiration), (2) from water bodies, and (3) from bare ground (Figure 5). In this case, the typical range is about $0.1 \leq K \leq 0.2$. For instance, in the vicinity of Ramona, in central San Diego County southern California, $K = 0.15$, confirming that K is highly dependent on the local climate.

Figure 5. Turner reservoir, central San Diego County, California.

Following nature's design, central values of K are more conducive to ecosystem health and ecological diversity. For $K \cong 0$, the system is stressed due to a lack of runoff and an excess of salts. For $K \cong 1$, the system is stressed due to too much runoff and a patent lack of vegetation. In theory, the ideal partitioning of precipitation should correspond to $K = 0.3$, i.e., roughly about one-third going to runoff and the remaining two-thirds to evaporation. In practice, this situation may approximately correspond to the middle of the climatic spectrum, which separates semiarid (on the dry side) and subhumid climates (on the wet side) (Ponce et al., 2000).

The preceding discussion has posited that very low runoff coefficients ($K \cong 0$) are very much the exception in naturally exorheic landscapes. A basin with a very low runoff coefficient generally leads to salt accumulation, since the scarce runoff is insufficient to transport all the salts. Basins with significant human settlement typically have yield runoff coefficients in the range $0.2 \leq K \leq 0.4$. This corresponds roughly to the semiarid to subhumid climates, where mean annual precipitation ranges between 400 mm (16 in) and 1 600 mm (64 in).

The Design of Man

In recent times, but more so over the past 100 years, humans have tended to settle semiarid and arid lands, where the available water may be insufficient to satisfy all needs, including natural and anthropogenic. The natural needs are those of the prevailing ecosystem, which requires water for its normal functioning. The anthropogenic needs are those imposed by human settlement, particularly for food, but also for domestic and industrial uses. For instance, the limit between semiarid and arid regions is 400 mm (16 in) of mean annual precipitation (Ponce *et al*., 2000). In a fully exorheic basin, this should roughly correspond to a yield runoff coefficient, K, of around 0.2. Often, this amount of water proves to be insufficient to satisfy all foreseen needs.

An anthropogenic use of water is its consumptive use for irrigation to produce food to satisfy the ever growing demand. Natural ecosystems are first in line to take up their share of water through evaporation and evapotranspiration; therefore, this amount is already committed. For humans, the only recourse has seemed to be the conversion of runoff to evapotranspiration by way of irrigation. This produces more food and other products, but at the cost of reducing the yield runoff coefficient (the consumptive use water in irrigation has to come from somewhere). Effectively, the additional food and other products produced has decreased the capacity of the basin to flush its salts.

There are those who argue that runoff water is too precious to waste it in the oceans. Under this misguided optic, every drop of rainfall that goes into runoff must be stored and directed to economic uses. Irrigation is of particular concern, because if developed without limit, it leads to the eventual disappearance of all runoff. In effect, when all runoff is converted to evaporation, the yield runoff coefficient decreases to zero, setting the stage for a salt-infested desert to take over (Figure 6).

Figure 6. Salinized irrigation field, Chao valley, Peru.

The solution is to implement appropriate regulations that limit the anthropogenic conversion of runoff to evapotranspiration. Irrigation must be limited to the amount that is absolutely necessary. It has been found that in semiarid and arid regions, where irrigation is most needed, the production of food results in less runoff, when in actuality,

more runoff is required to successfully accomplish the removal of the extra salts.

A lesson to be gleaned from the historic record is that of the little-known Hohokam civilization, which flourished in central Arizona for more than 1 200 years, until its unexplained disappearance around 1 450 A.D. (Figure 7) (Encyclopædia Brittanica, 2015). Floods, droughts, and salt accumulation have been used in an attempt to rationalize the demise of the Hohokam, which, quite fittingly, in the local Pima language means "those who have vanished" (Arizona Museum of Natural History, 2015). Salinity may stand out as the most likely culprit, since floods actually enrich the soil with fresh nutrients and droughts are often temporary. Moreover, salinity is pervasive and difficult to manage, particularly in an arid environment such as that of central Arizona.

Figure 7. Hohokam red-on-buff ceramics (Arizona Museum of Natural History, 2015).

The sustainability of irrigation has been thoroughly examined over the past two decades, notably by the ASCE Practice Manual No. 71 (American Society of Civil Engineers, 1990). On one side of the argument are those who advocate the return to dryland farming, which entails the abandonment of irrigation as a desirable human enterprise. The problem began with the settlement of arid lands, which humans

may have earnestly pursued in their search for more land, health, and sun. Barring the undoing of the settlement of arid lands, which at this juncture seems politically unrealistic at best, the only feasible course to take is the regulation of irrigation. It makes practical sense to reserve a portion of the runoff for the avowed purpose of flushing the salts out of the basin (Ponce, 2013). This appears to be the only sustainable course of action.

Basin Salt Balance

The concept of basin salt balance helps explain the conflict between the design of nature and that of humans. Nature intended for fully exorheic basins to be in salt balance, i.e., no net salt accumulation over time. On the other hand, endorheic basins are not in salt balance, undergoing a continuous process of salt accumulation over geologic time.

It is important to note that the actual drainage pattern may not always be clear. In some cases, in accordance with local geomorphology, basins may be semiendorheic or semiexorheic, depending on which process (salt collection or salt flushing) is more prevalent and to what extent. For instance, the Upper Paraguay River basin, located near the geographical middle of South America is an exorheic basin, for all intense and purposes, with a mean annual outflow of 1 565 m^3/s at its mouth, the confluence with the Apa River, in Mato Grosso do Sul, Brazil (Ponce, 1995). Yet, in some places the presence of salinas, or salt ponds, shows that not all areas of the basin are connected to the main drainage system (Figures 8 and 9) (Martins, 2012).

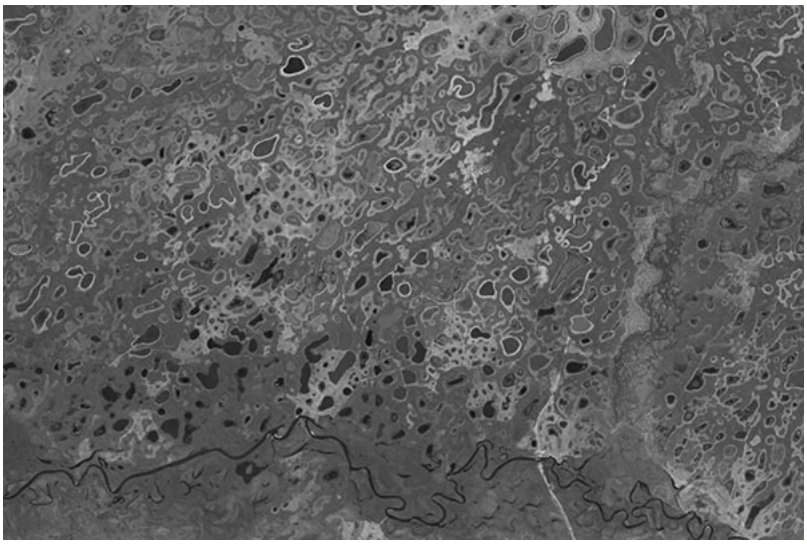

Figure 8. Aerial view of salt ponds near the Rio Negro, Mato Grosso do Sul, Brazil (Google Earth, 2015).

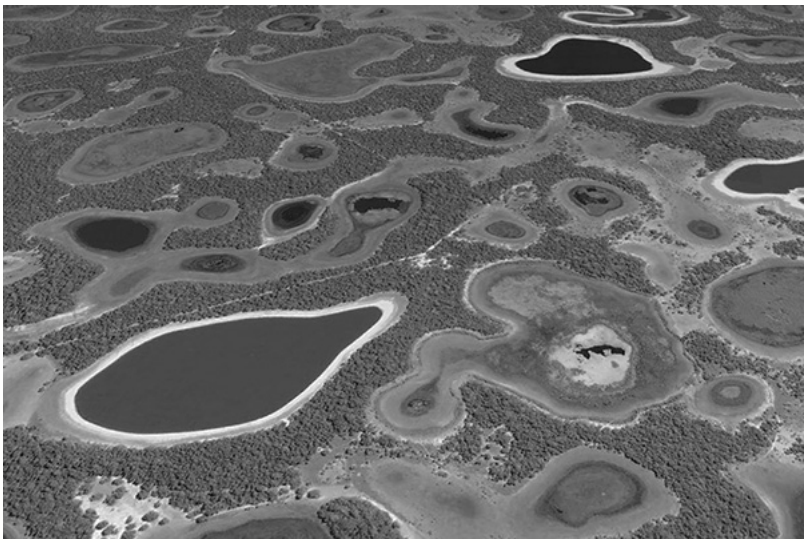

Figure 9. Closeup of salt ponds near the Rio Negro, Mato Grosso do Sul, Brazil (Google Earth, 2015).

In fact, while appearing to be in regional salt balance, the Upper Paraguay basin may actually not be in local salt balance. Thus, in continental-delta types of large subhumid basins, such as the Upper Paraguay, local geomorphology is found to have a crucial impact on endorheism.

The choice between exorheism and endorheism is clear. Since salts generally end up degrading natural ecosystems, particularly in

arid/semiarid regions, exorheic basins are to be preferred over endorheic ones. Preserving or conserving a basin's salt balance--presumably as close to pristine as is realistically possible--must be the overriding goal of sustainable basin management. The example of the Inland Empire Brine Line, in the Santa Ana River watershed, in California, shows that the goal is achievable (Santa Ana Watershed Project Authority, 2012). In this case, the basin's peripheral continental location clearly favored the salt balance objective.

The Case of the Tulare Lake Basin

A historic though somewhat extreme example of anthropogenic runoff (and salt) sequestration is that of the Tulare Lake basin, located near the southern tip of California's Central Valley. In the 1840s, at the onset of modern settlement in the area, Tulare Lake was the largest freshwater lake west of the Mississippi River, with the second largest surface area in the U.S. At an elevation of 216 ft (66 m), its highest flood level, recorded in 1862 and 1868, Tulare Lake spanned 790 square miles (2 040 km^2) (Figure 10) (ECORP Consulting, 2007).

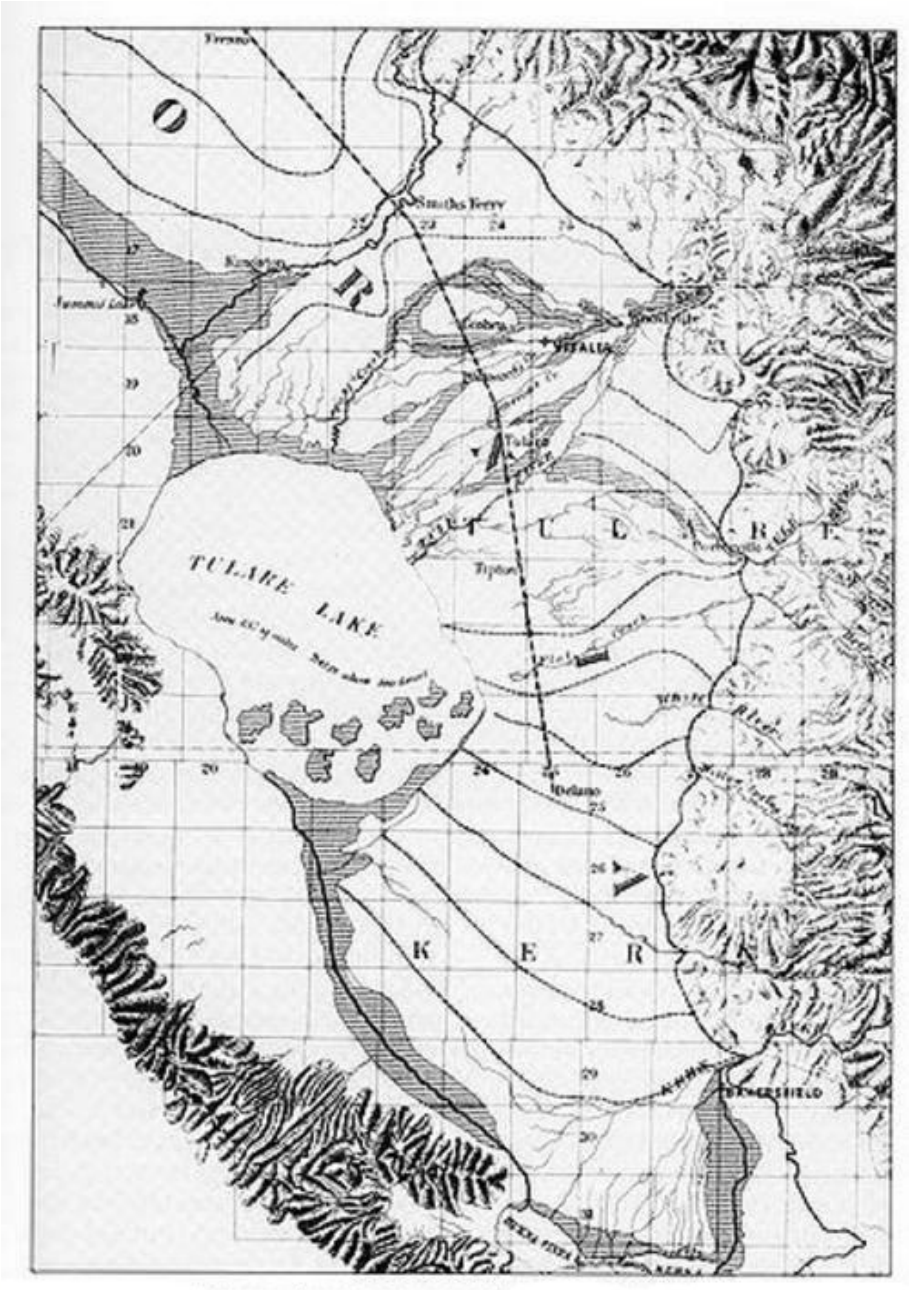

Figure 10. Tulare Lake basin, Central Valley, California (1874) (Wikipedia, 2015)

Through most of the 1800s, Tulare Lake functioned as a semiendorheic basin, collecting its own local and regional runoff from the South Fork Kings, Kaweah (Figure 11), Tule, and Kern rivers. During periods of infrequent flooding, at elevations above 207 ft (63 m), Tulare Lake would overflow northward, through Fresno Slough, into the San Joaquin River basin, flushing away a portion of its salts.

Figure 11. Kaweah River, tributary of Tulare Lake, California, USA.

Tulare Lake overflowed 19 times during a 29-year period, from 1850 to 1878. The total outflow during that period is estimated to be 1 055 000 acre-feet (ECORP Consulting, 2007). No overflows occurred after 1878 due to increasing diversions through tributary flows used for irrigation and municipal water. By 1899, the lake had dried up, except for residual wetlands and occasional floods.

Irrigation development in Tulare Lake basin has effectively meant that for about the past 137 years all runoff has been retained within the lake confines, and with it, all salts. In addition to the salts already present in normal amounts in natural runoff, the irrigation of arid lands effectively creates new salt wastes (of calcium and sodium) by disaggregating the relatively geologically young soils to extract the useful salts (magnesium and potassium) (Rhoades, et al., 1968). Thus, irrigation development represents a double whammy--less runoff available to transport the regional salts and more salt produced locally.

In the Tulare Lake basin, salts are stored in evaporation basins (Figure 12). In order to handle the increasing amounts of salt, an artificial waterfowl habitat has been used over the past several years (Figure 13). The effect of this massive salt collection operation on the surrounding environment, both above and below ground, remains to be elucidated.

Figure 12. South evaporation basin, Tulare Lake basin, California, USA.

Figure 13. Waterfowl habitat, Tulare Lake basin, California, USA.

Pillsbury (1981) has presented a bleak picture of the aftermath of salt collection in evaporation basins. He states that: "... Although the groundwaters under the evaporation basin may well be brackish or saline, every groundwater basin with a flow gradient must have an outlet somewhere near its lower end. The saline water in the evaporation basin will serve to increase the head, or hydraulic pressure, of the saline waters below, and will thereby increase the rate of discharge at the natural outlet, wreaking havoc on downstream groundwaters and downstream lands. If the evaporation basin is situated above soil that is knowingly impermeable to fresh water, the soil will gradually become more permeable when the waters are saline..."

The trade-offs of extensive irrigation development, particularly of arid lands, are patently clear. More food will be produced, but at the cost of additional salts, which will require appropriate disposal. Lack of proper salt management will render the irrigation system unsustainable over the long run. As Pillsbury aptly pointed out, it is a matter of time before the system will begin to show its cracks.

The case of the Tulare Lake basin may be an extreme example of anthropogenic salt sequestration, but it is by no means an isolated one. All irrigation development, particularly that of arid lands, will end up increasing either (a) the salinity of downstream flows or (b) the salinity of local groundwaters. (Pillsbury, 1981). Thus, the tradeoffs of irrigation development must be critically examined. In many cases, when all factors are carefully considered, the feasibility of irrigation development may prove to be elusive (American Society of Civil Engineers, 1990).

Conclusions

The following conclusiones are derived from this study:

The source of most ocean salts are lithospheric rocks. Salts have been transported to the oceans over geologic time by the flow of streams and rivers.

The biosphere retains most of the potassium and appreciable quantities of magnesium. The biosphere appears to have little need for calcium and sodium.

For every metric ton of weathered and eroded rock, about 55 kg of lithospheric salt cations are released into the hydrosphere.

The ocean is actually a sink for calcium, which is used by a variety of marine organisms for the construction of shells and skeletons.

Sodium is the only elemental salt cation that remains largely unused, even in the oceans. There is no biological process known to remove sodium from the oceans.

Rivers are the agents by which nature disposes of its salt waste. Effectively, rivers are seen to be natural exporters of salt to the oceans (Pillsbury, 1981).

Reducing river flow through irrigation has the net effect of gradually converting an exorheic drainage into an endorheic one, compromising the natural salt balance.

Central values of yield runoff coefficient are more conducive to ecosystem health and ecological diversity. The ideal partitioning of precipitation corresponds to $K = 0.3$, i.e., about one-third going to runoff and the remaining two-thirds to evaporation.

If developed without limit, irrigation leads to the eventual disappearance of all runoff. When all runoff is converted to evaporation, the yield runoff coefficient decreases to zero, setting the stage for a salt-infested desert to take over.

All irrigation development eventually ends up increasing either (a) the salinity of downstream flows or (b) the salinity of local groundwaters (Pillsbury, 1981). Thus, the tradeoffs of irrigation must be critically examined.

In summary, ions of sodium and calcium are produced by lithospheric disintegration in quantities far exceeding those that could possibly be assimilated by the terrestrial biosphere. In exorheic drainages, the resulting waste has been (and is being) transported to the ocean by streams and rivers. In endorheic drainages, it has collected in the interior of continents, producing closed salt basins. In general, exorheism is preferable to endorheism because it leads to healthier, more diverse ecosystems.

Irrigation development converts runoff into evaporation, reducing the amount of water available for salt flushing. At the same time, particularly in arid and semiarid regions, where it is most needed, irrigation mobilizes new salts through the additional biodegradation of geologically young soils (Rhoades *et al*., 1968). In the limit, when all runoff is sequestered and converted to evaporation, no runoff is left to carry the salts to the ocean. As the system is gradually driven towards this limit, it becomes unsustainable, not for lack of water to support the vegetation, but for lack of water to flush the salts.

In accordance with hydrologic science, we posit that nature had a different plan: on average, two-thirds of the available water for the ecosystem and the remaining one-third for the flushing of all salts, regional and local (new salts) (Pillsbury, 1981). The strategy of retaining most or all runoff, on the misguided grounds that it constitutes "precious" water, could only lead to the eventual conversion

of peripheral continental basins into salt-infested artificial basins. It appears most certain that this was not the design of nature.

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